AD-A180 191 EVALUATION OF GRAVITY DATA WITHIN THE DEPARTMENT OF DEFENSE GRAVITY LIBRARY(U) DEFENSE MAPPING AGENCY AEROSPACE CENTER ST LOUIS AFS MO K L HILLE JUN 87 1/1

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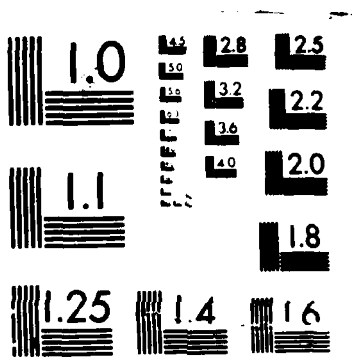

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SECURITY CLASSIFICATION OF THIS PAGE

AD-A180 191

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION: UNCLASSIFIED	1b. RESTRICTIVE MARKINGS: n/a
2a. SECURITY CLASSIFICATION AUTHORITY: n/a	3. DISTRIBUTION/AVAILABILITY OF REPORT: Unlimited Distribution
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE: n/a	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): n/a	5. MONITORING ORGANIZATION REPORT NUMBER(S): n/a
6a. NAME OF PERFORMING ORGANIZATION: Defense Mapping Agency Aerospace Center; 6b. OFFICE SYMBOL (If applicable): DSCT	7a. NAME OF MONITORING ORGANIZATION: n/a
6c. ADDRESS (City, State, and ZIP Code): 3200 S. Second St, St. Louis, MO 63118-3399	7b. ADDRESS (City, State, and ZIP Code): n/a
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: n/a; 8b. OFFICE SYMBOL (If applicable): n/a	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: n/a
8c. ADDRESS (City, State, and ZIP Code): n/a	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. n/a; PROJECT NO. n/a; TASK NO. n/a; WORK UNIT ACCESSION NO. n/a

DTIC ELECTE MAY 1 1 1987 A

11. TITLE (Include Security Classification)
Evaluation of Gravity Data Within the Department of Defense Gravity Library

12. PERSONAL AUTHOR(S)
Ms. Kathryn L. Hille

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical paper	FROM n/a TO	1987, June	44

16. SUPPLEMENTARY NOTATION
for publication in Bureau Gravimetrique International Bulletin D'Information Toulouse, France.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	
08	05		Gravity, Evaluation, DoDGL, Gravity Library

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The Department of Defense Gravity Library (DODGL) maintains an automated file of worldwide surface gravity observations. The gravity information in the database has been acquired from numerous sources including many scientific and government organizations, educational institutions, and private companies. To establish the quality of the gravity data in the database the data is subjected to review and evaluation and referenced to a common datum, the International Gravity Standardization Net of 1971 (IGSN 71). The data evaluation process is designed to eliminate duplicate data and reduce errors to a minimum. Error sources include instrument and recording errors, horizontal or vertical positioning errors, data correction (reduction) errors, and uncertainties in base station connections and the IGSN 71. Relationships and fit between individual data sets are also a consideration. Based on results from the evaluation process, gravity data is deleted, modified, or adjusted to obtain the most error free data possible. An accuracy value is assigned to each gravity observation based upon all findings from the evaluation. When the evaluation of a data set has been completed, the database is updated to reflect the evaluated data. Due to ongoing gravity data acquisition, evaluation is a continuing process.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL: Kathryn L. Hille	22b. TELEPHONE (Include Area Code): (314) 263-8398; 22c. OFFICE SYMBOL: DSCT

DD Form 1473, JUN 86 Previous editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED

87-5-7-031

Evaluation of Gravity Data

within the

Department of Defense Gravity Library

By

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June 1987

ABSTRACT

The Department of Defense Gravity Library (DODGL) maintains an automated file of worldwide surface gravity observations. The gravity information in the database has been acquired from numerous sources including many scientific and government organizations, educational institutions, and private companies. To establish the quality of the gravity data in the database the data is subjected to review and evaluation and referenced to a common datum, the International Gravity Standardization Net of 1971 (IGSN 71). The data evaluation process is designed to eliminate duplicate data and reduce errors to a minimum. Error sources include instrument and recording errors, horizontal or vertical positioning errors, data correction (reduction) errors, and uncertainties in base station connections and the IGSN 71. Relationships and fit between individual data sets are also a consideration. Based on results from the evaluation process, gravity data is deleted, modified, or adjusted to obtain the most error free data possible. An accuracy value is assigned to each gravity observation based upon all findings from the evaluation. When the evaluation of a data set has been completed, the database is updated to reflect the evaluated data. Due to ongoing gravity data acquisition, evaluation is a continuing process.

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INTRODUCTION

The degree of success of many projects which make use of gravimetric data and products is dependent on the quality and consistency of data in the Point Gravity Anomaly (PGA) Master File. The PGA Master File (or PGA Database) is an automated file of worldwide gravity observations. The sources of gravity information contained in the file cover a broad spectrum of the scientific and technical community. Scientific, government, and private organizations send to and exchange data with the Department of Defense Gravity Library (DODGL). Data sources include the United States Naval Oceanographic Office (NAVOCEANO), the Defense Mapping Agency Hydrographic/Topographic Center (DMAHTC), the National Oceanographic and Atmospheric Administration (NOAA), the Unites States Geological Survey (USGS), the geophysical exploration companies, universities and institutions involved in geodetic or geophysical research (national and international), state agencies, and agencies of foreign government [Boyer,1974].

A reconciliation or interrelation process is necessary to achieve commonality between data sets within the PGA Master File. To realize this homogeneity, gravity data accessioned to the PGA Database is subjected to examination and evaluation. The primary purpose for an in-depth evaluation of data is quality control. The procedures which constitute the task are designed to ensure gravity data placed in the PGA Database is of an acceptable accuracy, that all data is consistent, and that the most acceptable version of similar data sets accessioned [Scheibe et al., 1983]. As a result of this process, erroneous gravity data is removed from the database, identified systematic errors are removed, and all data is tied to the same datum.

All data sets sent to the DODGL are similar in nature. All contain data derived from observed gravity values. However, they are quite dissimilar since the data is collected from a variety of sources, has been surveyed at different times for different purposes under various environmental conditions, using various types of equipment, surveying procedures, and data reduction methods [Boyer,1974].

For evaluation purposes, the earth's surface is divided into regions corresponding to the areas covered by the 1:1,000,000 scale Operational Navigation Charts (ONC) produced by the Defense Mapping Agency Aerospace Center. The ONC areas are evaluated (more appropriately, re-evaluated) periodically. Frequency of evaluation is dependent on the amount of accession activity in the area as well as the current importance of the area (with respect to priority project demands). Determining the order in which ONC areas will be evaluated is a function of allocating the most important areas to the available manpower. Areas with a high degree of accession activity or project priority are evaluated more frequently [Scheibe et al., 1983].

The evaluation process consists of nine stages. These are: (1) assembly of gravity data, associated information, and evaluation aids, (2) knowledge of the surveying organization, (3) a general trend analysis of area and data, (4) elimination of duplicate data, (5) detection and resolution of errors, (6) gravity base station check, (7) estimation of survey accuracy, (8) updating processes,and (9) final operations. These stages constitute a "guideline" for the evaluator. However, cases frequently arise where it is advantageous to perform an evaluation out of any prescribed order. No two ONC areas are alike with respect to geologic structure, topographic setting, and distribution of gravity data. Therefore, no two evaluations are exactly the same. The actual sequence of an evaluation is largely a matter of judgment on the part of the evaluator [Scheibe et al., 1983].

ASSEMBLY OF GRAVITY DATA, ASSOCIATED INFORMATION, AND EVALUATION AIDS

Before beginning an in-depth examination of gravity data, the evaluator assembles materials and information that will be benefical in the evaluation. The information retrieved consists of gravity data from the PGA Master File, survey and source information, base station data, and other pertinent documentation.

Automated Materials

One of the major computer subroutines utilized in assembling data is the "Point Gravity Anomaly (PGA) Select" program. This computer program is designed to iterate through any PGA-structured input file selecting records which satisfy input criteria. Initially, PGA Select is used to retrieve from the PGA Master File all gravity stations falling within an ONC area. It is also used to create secondary, smaller sets of gravity data during the course of evaluation. Output is a file used continually throughout the evaluation process, primarily in updating and plotting.

A data listing is also generated. Information contained in the records retrieved for each gravity station include its geodetic position (latitude and longitude), the source number (a unique four digit code assigned upon acquisition of a data set), observed gravity value, elevation above mean sea level, free-air and Bouguer gravity anomaly values, and the assigned (if any) anomaly accuracies. Print options range in detail from listing only the total stations examined and retrieved to a listing by latitude of all records retrieved and a count of stations falling in each $1^o \times 1^o$ area.

A second source of information is the "Source File." The type of data stored on this file includes the geographic boundaries of the data set, the accession date, the total number of stations in the survey, the authors (the surveying organization)

and the contributing organization (organization sending the data to the DODGL), the title of the survey, and the survey date. A listing is produced by accessing the Source File through the "Gravity Source File List" program by inputting a file of source numbers encountered from the PGA Select.

A third file accessed is the "Reference Gravity Base Station (RBS) File." Information stored on this file includes the location of the gravity base station (both the position and the name), a country code, an adopted gravity value, station accuracy and elevation above mean sea level , the parent base, and a network reference. The "Gravity Base Station Select" computer program uses base station numbers generated by the PGA Select computer program to access the RBS File and produce a listing [Dotson and Reinholtz, 1975].

After generation of the products mentioned above, a "Source and Reference Base Station Comparison" is generated by execution of a computer program of the same name. The unique matching of source numbers and gravity base stations is used to produce a listing of the matches along with free-air and Bouguer gravity anomaly accuracies, if previously assigned.

Nonautomated Materials

Nonautomated documentary materials must also be gathered. ONCs, topographic maps, bathymetric charts, and geologic/tectonic maps are used for orientation, checking gravity station locations and elevations, and general analysis. The "Source File Fact Sheet" provides source and base station information. Attached to this sheet is a graphic representation of the source coverage. Previous "Evaluation Histories" (Evaluation Summary Reports) can be benefical in describing the ONC area, any problems encountered with any source, and the method used to resolve those problems. Evaluation Histories also include a

contour plot of the gravity data from the previously evaluated sources. These materials are collected before beginning the evaluation of a new source or are obtained on an "as needed" basis during the course of an evaluation.

Evaluation Aids

There are several evaluation aids produced that assist in the examination and evaluation of gravity data. The "Gravity Station Comparison" computer program creates a cross reference listing of collocated gravity stations within a tolerance set by the evaluator. It is a good check for common, near-common, and duplicate stations. This method of comparing individual sources to all other data on the file is useful because statistical information produced may make station differences and adjustments readily apparent.

A second aid is the output from a software package known as the "OSUCON Plotting" program. It is a graphics package originally designed by The Ohio State University (OSU). The graphic output is commonly referred to as "plots." Evaluators use the contouring capabilities to portray Bouguer gravity anomalies over land while free-air gravity anomalies are contoured when evaluating ocean gravity data. Various scales, contour intervals, and map projections are possible. The contoured plots can be produced in black and white or color. The figurative "work-horse" of the evaluation process is the "plot-by-source" subroutine. This subroutine works from a source-sorted gravity data file using information from the PGA Select program. The gravity station plot is produced in four colors with individual sources (their gravity stations) coded by color and symbol. The distribution and density of gravity data in an evaluation area mandate the scale and projection. An evaluator generally produces as many plots as needed to carry out a point-by-point inspection of the gravity station values in an ONC area.

Additional Information

Three additional sources of information may be beneficial in the gravity data evaluation process. All gravity-related material collected by the DODGL is stored in the "Source Document File." This material includes any data (heights or depths, gravity anomalies, positions, etc.) pertinent for the computation or recomputation of observed gravity value on the PGA Master File. The documents are retained in their original form at an off-line storage site. The material in this file is contained on aperture cards which are reduced, miniaturized versions of the original material. The Aperture Card File is stored within the evaluators' work area. The total holdings of the DODGL are also maintained in the work area as 1: 1,000,000 scale gravity station plots, reflecting the location of each station and its source.

KNOWLEDGE OF GRAVITY SURVEYING ORGANIZATIONS

Every evaluator should have an understanding of the surveying methods used by organizations providing gravity to DODGL. This is especially important within the ONC areas assigned to each evaluator.

Knowledge of the type of organization is very important. Is it a professional gravity surveying organization, a group of students, a research or geophysical company, or is the data from a state or federal program? Different organizations have different guidelines and standards concernings the quality and precision of the gravity data they acquire. For example, the number of internal checks performed and the amount of funds available influence data quality.

The objectives of the organization for obtaining gravity data is another point of interest. Is the gravity data being acquired to support academic research, a

federal gravity application program, oil or mineral exploration, or will the data be used simply to support a report (thesis, dissertation ...)? The objective of the gravity survey will generally determine the amount of time and effort that is spent on checks and other quality control measures.

The organization sending data to the DODGL may not be the organization that performed the gravity survey. If the organization is a clearinghouse for gravity data, and problems or questions arise, will it be capable of providing any answers to an evaluator?

An evaluator must have knowledge of the location of a survey. Were the observed gravity stations in areas of easy accessibility? How rough was the terrain? Was the ship in shallow or deep water? How were the positions for the stations determined: precisely or scaled from a map? How accurate are the maps or charts in the area? Have the stations been correctly located? By what method and to what accuracy have station elevations been determined? The answers to these questions reflect upon the accuracy of the survey.

Knowing what instruments were used to gather the data is important. New technology has introduced new instruments with increased capabilities. These tend to improve the accuracy of the data recorded. Each instrument (new or old) has parameters unique to itself and must be operated correctly.

Improved instrumentation (recording devices) and surveying techniques (transportation modes and methods) have increased the speed at which data can be gathered. The date of the survey often puts the techniques and instruments used within the proper timeframe.

GENERAL TREND ANALYSIS

A key factor in any gravity data evaluation is a thorough visual inspection of

the gravity anomaly contour plot. An evaluator checks the overall relationship of the gravity data to the ONC area and to itself. Questions raised which need to be answered are concerned with the continuity of the data. Does the general gravity field appear to fit the area? Are the lows and highs where expected? Do magnitude changes occur where they are warranted ? Are the land gravity stations indeed on land and the ocean gravity stations at sea?

In general, gravity anomalies directly reflect the land and ocean bottom surfaces. For example, on continents, the Bouguer gravity anomaly should be less than the free-air gravity anomaly and with increasing (higher) elevation usually becoming regionally more negative (lower magnitude). The type of topography present in an area (mountains, plains, etc.) will affect the gravity value and the gravity anomaly. Local geology such as rock type, block faults, sedimentary basins, etc. also influence the gravity anomaly value.

In ocean areas, there is a correlation between free-air gravity anomalies and the topography of the ocean bottom (bathymetry). For example, the gravity anomaly will show a rapid downward trend over trenches with a minimum near the trench axis. Along mid-ocean ridges, the free-air gravity anomaly values are uniformly more positive, by approximately 20 to 30 milligals, than those over the adjacent ocean floor. Over seamounts, the free-air gravity anomaly also becomes more positive as the apex is approached. There is generally a free-air gravity anomaly high near the edge of a continental shelf and a low along the base of the continental slope [Dehlinger, 1978]. This is called "the edge effect."

It is expected that the gravity anomaly field will show appropriate changes over the topographic and bathymetric surfaces. If an evaluator is aware of possible local irregularities in those surfaces, abrupt changes in the gravity field will not incorrectly be thought to be erroneous gravity data. An evaluator refers to available topographic maps or bathymetric charts of the area to check for features

that can be expected to produce changes in the gravity anomaly field.

ELIMINATION OF DUPLICATE GRAVITY DATA

Definition

Situations may arise where identical or nearly identical data sets are encountered. It is important to differentiate between duplicate data and common stations.

Common stations are gravity stations where two or more independent measurements (different surveys) have been made at or near the same site. The station positions and elevation are essentially the same. This situation arises most often when different surveys make a gravity measurement at the same elevation markers ("benchmarks"). This practice is designed to assist in maintaining vertical control throughout a given survey. It is not uncommon for intersecting or overlapping surveys to occupy a single benchmark station [Scheibe et al., 1983]. Duplicate data sets are data from two or more sources that are, for all intents and purposes, exactly the same. Latitudes, longitudes, and elevations of corresponding stations are so similar they are considered to be the same set of data.

Duplicate data sets result from reprocessing the same observational data set. The measurements are not independent. They may occur when an organization supplies the DODGL with a data set, but then performs any one of numerous modifications and re-submits the data at a later date, this time with the modifications. Or, an agency can submit a set of data, perform additional station readings over the area, and then submit the final data set. The first set of data will also be included in the second submission. A third method of acquiring duplicate data occurs when two or more organizations supply the DODGL with the same data. The

situation is complicated if one of the organizations furnishes the data with additional stations over the area or if any of the organizations modify the data in any way prior to submission.

Detection

Detecting and differentiating between duplicate data and common stations is aided by the plot-by-source gravity station plot. The plotting routine assigns a unique symbol to the records from each source in the ONC area. By referring to this plot an evaluator can discern where collocation or duplication occurs, the sources involved, and the extent to which it occurs.

The Gravity Station Comparison listing is also used in the identification of common stations and duplicate data. The routine lists, as mentioned previously, a cross-reference of facts for gravity stations which are located within a specified distance of each other. This includes the difference in gravity values for collocated stations. By using this listing an evaluator can determine whether the collocations are common to a degree indicative of duplication. This is detectable when most, if not all, stations from one source consistently collocate with another source. Identical geodetic coordinates, station elevations, and station sequence numbers occur in instances of duplicate coverage [Scheibe et al., 1983].

Resolution

In most cases, common stations demonstrating the desired consistency in gravity values are retained by the evaluator. This action assists in the determination of a correct gravity value in future evaluations where additional collocation may require a decision regarding source reliability.

Some of the duplicate data is discovered and eliminated prior to file accession. But more frequently, all data is placed on the PGA Master File and it is the evaluators' job to locate and eliminate the duplication.

Duplicate data can be resolved and eliminated in various ways. Elimination depends on whether the data was received from a collection agency or the original surveying organization, the extent of duplication, and the modifications performed and their validity. Final determination is left to each evaluator on a case by case basis.

When deciding which source or sources to delete (or a portion of a source), an evaluator attempts to retain a source in order to preserve its individuality rather than combining several surveys under one source number.

GRAVITY DATA ERRORS

An evaluator has the responsibility to locate, analyze, and when possible, rectify inconsistent gravity data within an ONC area. Inconsistent data takes the form of abnormal gravity values which cannot be explained by topography, bathymetry, or geologic structure [Scheibe et al., 1983]. The abnormal gravity values are considered to be errors. There are three general classes of errors: systematic errors, blunders, and random errors. Systematic errors are those errors which tend to follow some fixed "law", which may be unknown. This error occurs with the same sign and often with a similar magnitude. A blunder can be defined as a gross mistake. Blunders are generally caused by carelessness. The residual errors, the errors remaining after all other errors have been eliminated or resolved, are considered random errors [Greenwalt and Shultz, 1962; DoD Glossary, 1981].

A primary task of gravity data evaluation is the detection and elimination, if possible, of all known systematic errors and blunders so that any unresolvable but

uneliminated are random in nature. These random errors, often small in magnitude, are then reflected in the accuracy values assigned to the gravity data.

Error Sources

There are numerous error sources within gravity data sets. These include instrumental errors, recording and transcription errors, positioning errors, datum errors, and errors in the surveying procedures [Woollard, 1967 : Boyer, 1974: Scheibe et al., 1983].

Horizontal positioning errors directly propagate into gravity anomaly errors. The horizontal position error has a north/south sensitivity of 1.3 sin $2\emptyset$ mgal per statute mile, where $\emptyset$ is the geodetic latitude of the gravity station. (This is equivalent to 1.5 sin $2\emptyset$ mgal per arc minute of latitude. These values are found by derivations of the normal gravity formula.) Longitudinal errors may also occur, although they will not be directly evident in erroneous gravity anomaly values. The geodetic coordinates of the gravity station may have been determined using misread instrument measurements or from an incorrectly scaled map or chart. A station may have been improperly identified leading to an erroneous location. Horizontal positioning errors may take the form of transposed digits, misaligned decimals, or the use of incorrect signs with the coordinate (wrong hemisphere or quadrant).

Gravity station elevations, with respect to mean sea level, are determined by conventional (spirit) leveling, map and chart interpolation, altimetry (barometric), or trignometric leveling. Each elevation determinaton method has different accuracy limitations. Vertical positioning errors are created when map or chart information is unreliable or is incorrectly interpolated. When other methods are used, errors are due to instrument mishandling or misreading, or by erroneous interpretation of the measurements. A vertical positioning error may also be due to the use of

incorrect elevation units. Errors can also be made when converting feet to meters, feet to fathoms, or meters to fathoms. The errors have a tendency to occur in areas of low elevation or shallow water where a small change in gravity anomaly magnitude is visible after a unit conversion is performed. In addition, errors can occur if a conversion is not made where necessary or if a conversion is applied twice.

A large group of gravity data errors are created by instrumental difficulties. A "tare" is defined as a disruption or rent in a data set. Tares are created by gravimeter malfunction. Improper handling of the instrument will cause abnormal readings. The gravimeter could have been dropped or jarred. It could have stopped (off heat), become stuck, or it could simply have been misread. Other errors may be due to off-leveling effects or poor calibration. Effects from vibration or magnetics may be included. Atmospheric effects such as pressure and temperature disturb instrument measurements. Many other types of instrumental error are possible [Woollard, 1967].

Survey procedures and techniques are a possible source of error. Measurement patterns, such as the loop or leap-frog technique, should have been followed. A gravity survey should have a number of reference points. Inaccurate or insufficient ties may lead to errors. Although an evaluator cannot and does not presuppose improper surveying methods, he/she must be aware of all possible causes of inconsistent gravity data.

Gravity survey measurements include corrections for instrument drift, luni-solar effects, and vehicle movement (e.g., the Eotvos correction in ocean data). If any of these corrections are applied incorrectly or inaccurately, errors are created.

Gravity data errors are also due to incorrect datum referencing. These types of errors are generally synonymous with a gravity base station error. A gravity base station error may be created by using an incorrect reference value. The

value may have been overly corrected, under corrected, or double corrected to comply with the present reference system (IGSN 71). A datum referencing error is commonly called a "datum shift."

Error Detection

The detection of abnormal gravity values is largely a manual process requiring an evaluator to visually inspect a gravity anomaly contour plot. Erroneous gravity values, reflected in the anomalies, may be apparent on the contour plots where abrupt isolated changes of the gravity gradient immediately surrounding the suspect data will cause irregularities (a non-smoothness) in the contouring pattern. (See Figures 1 and 3.)

Horizontal positioning errors have a tendency to show as skews in the contour pattern. Station alignment is usually along lines of communication in land surveys. The majority of surveys follow roads, railroads, streambeds and shorelines. Alignment may also be in a gridded or linear pattern. This is often the case with ship survey tracks. Misalignment of survey tracks at sea or traverses on land may be evident with the aid of color and symbol coding of individual sources on the gravity anomaly contour plots. Additionally, number sequencing of gravity stations within a source may be indicative of misalignment. Irregularities in sequence numbers within traverse lines, or track numbers within ocean surveys, may occur without reason and the stations in error, those belonging in the break area, are found elsewhere on the plot.

Positioning errors are often difficult to locate using contouring alone. For example, a misplaced point may have an anomaly value that, by chance, fits into the gravity anomaly pattern at its erroneous location. A comparison between a PGA Select listing and a source's original data listing may be necessary.

Elevation errors may be difficult to detect. When an elevation error is present, the gravity anomaly will appear to be larger or smaller than expected for the gravity station elevation or depth. Referral to topographic maps or bathymetric charts is necessary. The gravity anomalies should be manually computed and compared to the values given on the PGA Master File. Common stations are also checked for discrepancies using the Gravity Station Comparison listing.

Gravity stations subjected to the effect of tare are usually found visually on the gravity anomaly contour plot due to unusual patterns in the contouring produced as a result of the effect of the error on the gravity anomalies. A tare could appear as a sudden change in anomaly values from one station to another within the same survey traverse. Or, the gravity anomalies along a traverse will all have the same value, indicative of a possible stuck gravimeter.

A scale change error is discovered by having numerous comparisons of near-common or common stations between a "new" source and previous, reliable, evaluated sources [Estes, 1971]. The new source's observed gravity value may agree with another source's value at one station or ship track crossing but the gravity differences will tend to increase or decrease along the survey track as the new source continually crosses the reliable sources. Scale changes are caused by the instrument, and are due to spring or calibration problems.

Datum shifts may be apparent from an inspection of the gravity anomaly contour plot. The contour pattern will change as a shift is encountered. This is dependent on the scale of the plot, the contour interval used, and the magnitude of the errors. The resultant, general pattern will be a group of contours set within smoother surrounding contours. (See Figures 1 and 2.)

Limitations within the contouring subroutine algorithm prevent some or all of the abnormalities from being reflected in the contour pattern. This may require the evaluator to inspect the gravity anomaly value at each data point (gravity station)

annotated on the plot. This is done visually and with the aid of listings from the Gravity Station Comparison and PGA Select computer programs. Topographic maps or bathymetric charts are also referenced. A source's orignal data listing is used to verify station positions and observed gravity values.

Resolution

It may be possible to correct positioning errors, both horizontal and vertical, when a correction is apparent and justifiable. Justifiable meaning, if corrected, the data will fit the general trend. With some positioning errors, a valid assumption or the cause of error cannot be made and no correction is possible. In such instances, the gravity stations are deleted from the evaluator's data file.

A tare is an instrumental error that is more often than not unresolvable since the exact cause of the error is untraceable. In such cases, the gravity stations affected by the tare are deleted.

The Gravity Station Comparison listing can be beneficial in detecting scale changes, datum shifts, and other systematic errors. Common and near-common stations are cross-referenced and the differences between the Bouguer and free-air gravity anomalies at such stations are noted. Variations in the magnitude and consistency of the difference may be indicative of an error. Many times the gravity anomaly difference between common stations is used as the adjustment or correction to be applied to all gravity stations within a source. At other times, the datum shift can be determined graphically from the contour plot.

Gravity station differences for common or near-common stations, when analyzing ocean gravity data, are usually found by comparing ship track crossings from a new source and a reliable, previously evaluated source. Numerous comparisons are needed to make a valid adjustment. When the track crossing differences are consistent in

magnitude and direction, an adjustment is made to the new source's observed gravity values by the addition or subtraction of that difference. Again, this adjustment may be applied to an entire survey or to only the stations along a particular track. If the track crossings are inconsistent in magnitude, but similar in direction a scale change error may be evident in the data. An evaluator will need to refer to the observed gravity values for confirmation. If a scale change is verified, a Least Squares Adjustment may be utilized to correct the gravity values [Estes, 1971]. When a scale change is not evident, the gravity stations along the survey track(s) are considered to simply be "bad" stations and are deleted from the evaluator's working file.

A typical datum shift an evaluator encounters is the translation of data from the Potsdam Reference System to the IGSN 71. The reference gravity base stations used for the gravity data in the DODGL are IGSN 71 stations. When Potsdam RBS values have been used by the surveying organization, the source's gravity stations must have an adjustment applied in order to convert the values to IGSN 71. The nominal correction applied is -13.7 mgals. But, in specific cases, the actual value of the correction may differ somewhat from the nominal value. This correction is normally applied to the gravity data by pre-accession analysts, but it may be overlooked or not be readily apparent in which case the final adjustment or "fitting" of the data to the IGSN 71 is left to the evaluator. (See Figures 1 and 2.)

Another example of a systematic error is in data sent in by geophysical exploration companies. Such companies are primarily interested in the small differences that occur between gravity values from point to point over a survey area. For that reason, the companies may establish their own referencing systems. These systems are not based or related to any national or international system (Potsdam, IGSN 71, etc.), although occasionally they are referenced to a normal

(theorectical) gravity value. The company is only concerned with the magnitude of the differences in gravity values at field stations from values at established starting points. The values of gravity at these starting points usually are not referred to the same gravity datum. Datum changes generally occur with respect to latitude. These pre-established values essentially create numerous "floating" datums within one source. In order to resolve the discrepancies between an arbitrary datum and the IGSN 71, the starting point value must be determined using common stations or gravity anomaly map comparisons. This problem may be originally discovered by pre-accession analysts, but it may be the evaluators' job to complete the gravity data adjustment.

Most systematic errors can be corrected in some manner and the corrected data retained on file. One type of systematic error that always requires deletion of the stations involved occurs due to "ship cornering." Although survey tracks at sea appear linear in form, readings are continuous throughout a ship's turn (changing direction). Errors occur during the turns due to acceleration problems. These errors are reflected in the measured gravity values collected during the ship's change of course. The existence of this erroneous gravity data in a data source will be apparent from changes in the contour patterning. In most cases, the organization performing the gravity survey will delete the turn stations prior to forwarding their data to the DODGL. However, sometimes all or part of the data gathered during the ship's course change is still present. The "bad" stations at the turns are identified by noting when the readings fluctuate from readings preceding and following the turn. The gravity measurements stabilize once the ship is back on course. The erroneous gravity stations are deleted from an evaluator's working file.

Sometimes, the "new" unevaluated gravity source receives an adjustment with the adjustment based on its fit and relationship to other data in the area, i.e. gravity

data that has been previously evaluated (the "old" sources). Othertimes, the unevaluated source may tie and correlate better to the area (geologically, topographically, and geophysically) than previously evaluated sources. In such cases, the previously evaluated sources are re-evaluated, an adjustment performed if necessary, and new gravity anomaly accuracies assigned if warranted. The determination that a new gravity source is more accurate than one previously acquired is dependent upon the quality of the survey: the date, the organization, the instrumentation and survey methods used, etc. (See section titled "Knowledge of Gravity Surveying Organization.")

If an error is found during the gravity data evaluation process an attempt is made to correct it. The correction or adjustment should bring the data set into proper fit with the surrounding gravity field. (See Figure 4.) When the data is not correctable or an error is untraceable, the data is considered for deletion. An unresolved error is often considered a blunder and portions or all of a source are sometimes deleted. (See Figure 5.) However, the need for coverage and station density may force the stations in question to be retained. When this occurs, the anomaly accuracies assigned to the gravity data reflect the presence of the unresolved error.

GRAVITY BASE STATION CHECK

A gravity base station is a reoccupiable station having an accepted value of observed gravity. A gravity base station check is performed to verify that each gravity source is referenced to at least one base station and the base station is referenced to the IGSN 71.

Ideally, the information necessary for verification includes the station name and number (Bureau Gravimetrique International, BGI: or DOD), the geographic

location, and the gravity value obtained, or used, during the survey. The ideal is not always attainable. Many gravity sources may include only a portion of the information while others may not provide any information. Source documents, aperture cards, other reference materials, and the DOD Gravity Base Station File are utilized and analyzed for base station verification. These materials are also used to establish the relationship between the survey value and the IGSN 71 value, if the latter exists.

In ideal situations, verification of a base station and its value is relatively simple. When documentation exists for the value of the field base station, an evaluator has only to check the difference (if any) between this value and the corresponding IGSN 71 value. Verification is made that the difference has been applied to all stations in the source [Scheibe et al., 1983]. When multiple base stations are used in the survey, the evaluator must verify that appropriate adjustments were correctly applied to corresponding segments of the survey.

A typical occurrence is when a field base station is referenced to the Potsdam System. All gravity stations in the survey must then be adjusted in order to reference them to the IGSN 71. (See section titled "Detection of Errors", datum shifts.) Generally, surveys made prior to the early 1970's were referenced to Potsdam. Many, but not all gravity surveys made since then are on the IGSN 71. (See section titled "Detection of Errors", geopysical companies.)

Data verification is complicated when the gravity sources do not provide complete information. Surveys may be referenced to gravity base stations not included in or tied to the IGSN 71. The gravity survey documentation must be analyzed in an attempt to locate base stations common to both the survey network and the IGSN 71, and to determine an adjustment relationship. The DOD gravity base station assigned to the source by the evaluator and the information describing the indirect tie to the field gravity base station is included in the evaluation

History. (See section titled "Final Operations.")

Instances occasionally occur where an organization does not provide any associated information with the gravity data forwarded to the DODGL. Therefore, no identifiable field gravity base station exists. However, it may be possible to use the Gravity Station Comparison listing to assign a base station value to the source based upon station commonality with other sources. In some cases, a reference gravity base station cannot be assigned.

All efforts are made to establish a base station for the gravity data. The source and related documentation search is exhaustive and if possible, the surveying organization is contacted and additional information requested.

GRAVITY ANOMALY ACCURACY ESTIMATION

Gravity anomaly accuracies are a function of the factors affecting gravity anomaly computation. These factors are related to both theoretical and observed gravity. Errors due to theoretical gravity are those due to uncertainties in the position (geodetic latitude) of the gravity stations. The errors contributed by observed gravity are functions of the errors that may occur in all aspects of accomplishing the observations. These include gravimeter malfunction, calibration errors, data recording errors, surveying procedures, positioning errors, elevation errors, and any other blunders or tares.

Land Gravity Surveys

For land gravity surveys, the accuracy of Bouguer gravity anomalies is of primary importance. The general equation for the accuray of the Bouguer gravity anomalies, based on the uniform incorporation of all factors influencing the

accuracy, has the form :

$$\sigma^2_{BA} = \sigma^2_1 + \sigma^2_2 + \sigma^2_3 + \sigma^2_4 \qquad (1)$$

where:

σ_{BA} = Bouguer gravity anomaly accuracy (on land).

σ_1 = Gravity Base Station accuracy, obtained from the RBS File. The RBS accuracies are based upon the errors in the absolute datum and the accuracy with which the Gravity Base Station is tied to the IGSN 71. Its value usually ranges from $\pm$ 0.2mgal to $\pm$1.0 mgal (1 sigma), although some base station accuracies are larger than $\pm$ 1.0 mgal.

σ_2 = Internal accuracy.

The following errors are incorporated within an internal accuracy value:
(1) instrumental errors related to instrument type, its calibration, and pressure and temperature effects;
(2) errors in the adjustment to a Gravity Base Station such as the number of ties to the station, the length of the survey, and the method of the survey;
(3) the reliability of survey and computation procedures which are dependent upon the purpose and date of the gravity survey, the organization, the instruments used, and the techniques utilized. The internal accuracy generally does not exceed $\pm$ 1.0 mgal.

σ_3 = (kh)

where:

k = A constant, 0.1967 [Heiskanan and Moritz, 1967].

h = Accuracy of gravity station vertical position (elevation).

This value is dependent upon the errors in the methods used to determine the height of the gravity station above mean sea level. Elevations determined by conventional (spirit) leveling are more accurate than elevations obtained by trignometric leveling, altimetry, or interpolated from topographic maps. The quality of the gravity station elevation has the most effect of the error sources on the overall accuracy of the gravity anomaly. For example, the difference between an elevation accuracy of $\pm$ 5 meters and $\pm$ 10 meters, with all other variables remaining constant, will change the accuracy of a Bouguer gravity anomaly on land by 1 mgal.

$\sigma_4 = (np)$

where:

n = The change in theoretical gravity per minute of geodetic latitude.

This value is tabulated and available to the evaluator.

p = Accuracy of gravity station horizontal position (geodetic latitude).

The error in geodetic latitude is determined by knowing the horizontal geodetic datum involved, the surveying method(s) used to determine the gravity station position, or the map accuracy, if the position of the

gravity station was interpolated from a map.
[Greenwalt and Shultz, 1962; DODGL communications, 1985].

Often an error value can not be reasonably assigned to some of the variables in the above error equation. In such cases two other approaches to accuracy determination are available for use. One is considered to be an Indirect Method, the other is call the Logical Method.

The Indirect Method utilizes a known error (the accuracy of other sources) and common stations. The error equation for the Indirect Method is :

$$\sigma_{BA}^{2} = \sigma_{K}^{2} + \sigma_{\delta\Delta g}^{2} \qquad (2)$$

where:

σ_{BA} = Bouguer gravity anomaly accuracy (on land).

σ_K = A known error in other gravity anomalies (the best accuracy of any source), frequently taken as the mean of known accuracies of all evaluated gravity sources in the area.

$\sigma_{\delta\Delta g}$ = Standard deviation of the differences of common gravity stations.

$$\sigma_{\delta\Delta g}^{2} = \sum_i (\delta\Delta g_i - \overline{\delta\Delta g})^2 / (n-1)$$

where:

$\delta\Delta g$ = The difference between gravity anomalies at a common station.

$\overline{\delta\Delta g}$ = The mean of the differences.

n = The number of stations in the comparison.

[Greenwalt and Shultz, 1962; DODGL communications, 1985].

The Logical Method involves numerous factors, but is not mathematically formulated. It relies on estimating the accuracies based on all influences acting as a whole. These influences include the survey date, the reputation of the organization, the type of survey instrumentation used, the method of determining positions and elevations, and the relationship of the gravity anomalies to the terrain and to other sources in the same area.

It is desired that Bouguer gravity anomaly accuracies range between $\pm$ 1 and $\pm$ 5 mgals. For error magnitudes larger than $\pm$ 5 mgals the, gravity data may or may not be usable depending on project requirements and the geographic area of interest.

To compute the accuracy of the free-air gravity anomalies for land data, the constant "k" in Equation (1), the Direct Method, is taken as 0.3086. When using the indirect or logical approaches, the product of elevation accuracy and the Bouguer plate constant, 0.1119, (which is also the difference between 0.3086 and 0.1967) determines the value to increase the Bouguer gravity anomaly accuracy to obtain the free-air gravity anomaly accuracy.

Ocean Gravity Surveys

For ocean gravity data, the free-air gravity anomaly accuracy is of prime importance. The "direct" formulation is inadequate for estimating the accuracy of ocean gravity data because it does not contain an expression for errors related to

the Eotvos effect. The Eotvos correction is a significant source of error in ocean gravity surveys. The correction must be applied in the reduction of gravity data taken from moving platforms (the ship) to obtain observed gravity values. The correction accounts for the gravitational effect of the motion of the ship with respect to the rotating earth. Uncertainty in latitude, velocity, and azimuth will create errors in the correction value. The form of the gravity data seen in the DOD Gravity Library does not lend itself to an analysis of any inaccuracies related to the Eotvos effect [Boyer, 1974].

This leads to a modification of the direct approach. The basis for the approach lies in three assumptions: (1) that the differences in gravity anomaly values at ship track crossings are the results of combined errors in gravimetry and navigation: (2) that the errors associated with each gravity anomaly value in the survey form a normally distributed population; and (3) that the differences at crossings, considered as errors , are a statistical sample from that population. The three assumptions allow the use of a simplified version of the direct equation, namely the indirect approach. The expression related to track crossings results from considering that h=0, that internal accuracy (i) is related to gravimetry accuracy, and that position and Eotvos error are related to navigation error. [DODGL comunications, 1985] The indirect method involves the known error, as in land gravity surveys, with the common station factor being replaced by a ship track crossing factor based on the above assumptions. The error equation for the oceanic free-air gravity anomalies has the form :

$$\sigma^2_{FA} = \sigma^2_{K} + \sigma^2_{\delta\Delta g} \quad (3)$$

where:

σ_{FA} = free-air gravity anomaly accuracy (ocean data).

σ_K = Known error (the best accuracy of any source), frequently taken as the mean of the known accuracies of all evaluated gravity sources in the area.

$\sigma_{\delta\Delta g}$ = Standard deviation of the gravity anomaly differences at ship track crossings.

$$\sigma^2_{\delta\Delta g} = \sum_i (\delta\Delta g_i - \overline{\delta\Delta g})^2 / (n-1)$$

where:

$\delta\Delta g$ = The difference between gravity anomalies at the ship track crossing.

$\overline{\delta\Delta g}$ = The mean of the gravity anomaly differences

n = The number of ship track crossings used in the comparison.

[Greenwalt and Shultz, 1962: DODGL communications, 1985].

The Logical Method used to assign accuracies to ocean gravity anomaly data involves all the factors and influences used with land gravity data. For ocean gravity surveys, the instrumentation used for navigation is also of concern and the gravity data is correlated with the bathymetry instead of terrain.

The accuracy of oceanic gravity anomalies will tend to be larger (worse) than the accuracy of land gravity anomalies. This is due to higher error tolerances being allowed for ocean gravity data with respect to the corrections applied for

uncertainties in navigation, cross-coupling, and the Eotvos effect. For ocean gravity data, free-air gravity anomaly accuracies range from ± 2 mgals to as much as ± 20 mgals.

UPDATING PROCESS

Types of Alterations

Any correction or modification to a gravity station or group of stations in an ONC area may be made as they are discovered. Or, all data alterations may be applied at one time. Many evaluators feel it is safer and less complex to perform the modifications a few at a time, as an ongoing process, throughout an evaluation. Modifications are made to the ONC area file using data updating subroutines.

Typical revisions to the ONC area file include deletion of individual stations from a single source or multiple sources, deleting a group of stations from a source, deletion of an entire source, corrections to stations, either individual or a group (A delete/add. This includes non-routine corrections such as depth corrections. Depending upon the area encompassed, an evaluator or a pre-accession analyst may be the responsible party.), performing a datum adjustment, performing a scale adjustment, adding or correcting a gravity base station, or assigning free-air and Bouguer anomaly accuracies [Dotson and Reinholtz, 1975].

Procedure

The Department of Defense Gravity Services Branch utilizes both a Digital Equipment Corporation VAX 11/780 Computer and a Sperry 1100 Series Computer. Whereas the functions are similar between the VAX 11/780 and the Sperry 1100 computer

programs, the difference lies in the format of the input data. The Sperry 1100 programs use PGA-structured files as input. The VAX 11/780 programs must be accessed by using a "Select File", a 23-word-per-record unformatted file. There are presently four computer programs utilized when updating an UNC area file.

The "Point Gravity Anomaly Edit-Sort" computer program consists of two separately execute subroutines. The edit phase checks data input for valid characters and format. These edited records are then sorted in the sort phase according to sorting criteria: by quadrants, within each quadrant, then by eight degree bands of latitude, etc. The sort phase may immediately follow an edit phase, or the edited data may be sorted at a later date.

The sorted data from the PGA Edit-Sort is utilized as input into the "Point Gravity Anomaly Update" computer program. This program uses the data to create changes to an UNC area file. These changes are commonly in the form of gravity record deletions and additions. The changes are reflected in the sorted data records.

Evaluators also utilize the delete capabilities of the "Point Gravity Anomaly Merge/Delete" computer program to delete gravity records from an UNC area file. Deletion is accomplished by source and/or geographic area. This is often referred to as "block deletion."

Gravity station modifications are performed with the "Point Gravity Anomaly Maintenance" computer program. Modifications involve datum adjustments, updating reference base station information, and assigning accuracies to the free-air and Bouguer gravity anomalies [Dotson and Reinholtz, 1975].

Table 1 gives the type of alteration and the most commonly utilized program sequence.

Table 1. Computer Programs Used in the Updating Process

PROGRAM SEQUENCE	TYPE OF CHANGE	COMPUTER PROGRAM
1	Deleting individual stations	a. PGA Edit-Sort and PGA Update b. PGA Maintenance (if only a few stations are involved)
2	Deleting part of a source or an entire source	PGA Merge/Delete
3	Correcting individual stations	PGA Edit-Sort and PGA Update
4	Datum adjustment	PGA Maintenance
5	Scale adjustment	A Least Squares Adjustment, then PGA Edit-Sort and PGA Update
6	Updating RBS information	PGA Maintenance
7	Assigning gravity anomaly accuracies	PGA Maintenance

FINAL OPERATIONS

Packaging

When an evaluator is satisfied that all updating has been completed in an ONC area, preparations are made to finalize the evaluation. This entails the assembly of all materials and information to be forwarded to the immediate supervisor for checking. The materials needed to update the PGA Master File are then forwarded to the DOD Gravity Services Library Section.

First, a gravity anomaly comparison, or "differences", program is executed. This computer program, The "Point Gravity Anomaly Compare", compares the final ONC area PGA-structured file to the original ONC area file. The output from this comparison lists the sources that underwent any updates and the types of modification performed. This list enables the evaluator to ascertain that all desired alterations to the ONC area file have indeed been performed.

A check is performed on the final data file using the computer program "Point Gravity Anomaly Sequence Check." This program checks the final, evaluated stations for proper sorted order (sequence) and format to successfully update the PGA Master File. The check also detects those records with geodetic positions outside the legitimate boundaries of the ONC. At the user's option, the computer subroutine can be used to build a new ONC area PGA-structured data file, omitting records which are out of sequence or that have unacceptable geodetic coordinate [Dotson and Reinholtz, 1975].

As a final check, the Source and RBS Comparison Program is executed. The computer program lists the source number, the RBS, the total number of gravity stations, and the assigned gravity anomaly accuracies for all sources on the final ONC area data file. This listing allows the evaluator to verify that all sources

have indeed been evaluated. This is apparent by the presence of gravity anomaly accuracy values. Gravity base stations are also checked for proper assignment.

Using the final ONC area file and the OSUCON plotting software, a gravity anomaly contour plot is produced. Such a plot simply shows the gravity anomaly contours. If desired, a four color, symbol coded, annotated gravity station plot can be made. If mandated by the number of stations or their density, numerous contour plots can be produced at scales that will allow illustration of individual stations.

When all details of the evaluation have been resolved a report is compiled. The "Gravity Evaluation Summary Report" is a written history of the ONC area gravity data evaluation. A geographic and geologic description of the area is included with a narrative of all sources in the area. This narrative, by source number, includes background information on each source (i.e., the author, survey date, instrumentation, type of navigation, survey procedures, RBS information, etc.) and a list of all modifications or alterations performed on the data (within each source). All actions performed and any conclusions or recommendations are described.

The aforementioned materials (the PGA Compare, the PGA Sequence Check, the final Source and RBS Compare listings, the final ONC area plot(s) of gravity anomalies, and the Gravity Evaluation Summary Report) are packaged together. The original Gravity Source Select List and Source and RBS Comparison listings are also included in the history package. These two listings document the sources selected from the PGA Master File at the time of initial retrieval. The ONC and other maps and charts used in the evaluation process are also packaged. An evaluator forwards this package to one of the Evaluation Managers (A Section Supervisor.)

All actions and operations taken over the course of the evaluation are reviewed and justification stated. After the supervisor is satisfied that all aspects of the

evaluation were performed acceptably, the final ONC area file number or name (as appropriate), the original Source and RBS Comparison Listing, the geographic boundaries of the ONC, and the PGA Sequence Check are forwarded to the PGA Database Manager. The remaining materials in the history package are maintained in storage for historical and reference purposes.

PGA Master File Updating

The final step in the gravity data evaluation process is the responsibility of the Database Manager. Upon receipt of the final ONC area data file the Database Manager will delete data from those sources initially retrieved from the PGA Master File by the evaluator. Limiting the deletion process in such a manner ensures that any new data accessioned after the initial retrieval will be left intact. In the same operation, data on the final data file is merged into the PGA Master File. Both the deletion and merging processes are performed by the PGA Merge/Delete computer program [Scheibe et al., 1983].

Upon completion of the merge/delete process, the affected gravity data sets now contain newly evaluated or re-evaluated data. At this point, the gravity data evaluation process is considered to be complete. The data in the PGA Master File covering the evaluated ONC area is now commonly referenced and is an adjusted representation of the data in the area.

The dynamic nature of the PGA Master File seldom permits this up-to-date status to remain for long. On-going gravity data acquisition necessitates a periodic review of the ONC areas. The frequency of review is determined by accession activity and project priorities. It is important to keep in mind that the end product of any evaluation process is temporary rather than permanent [Scheibe et al., 1983].

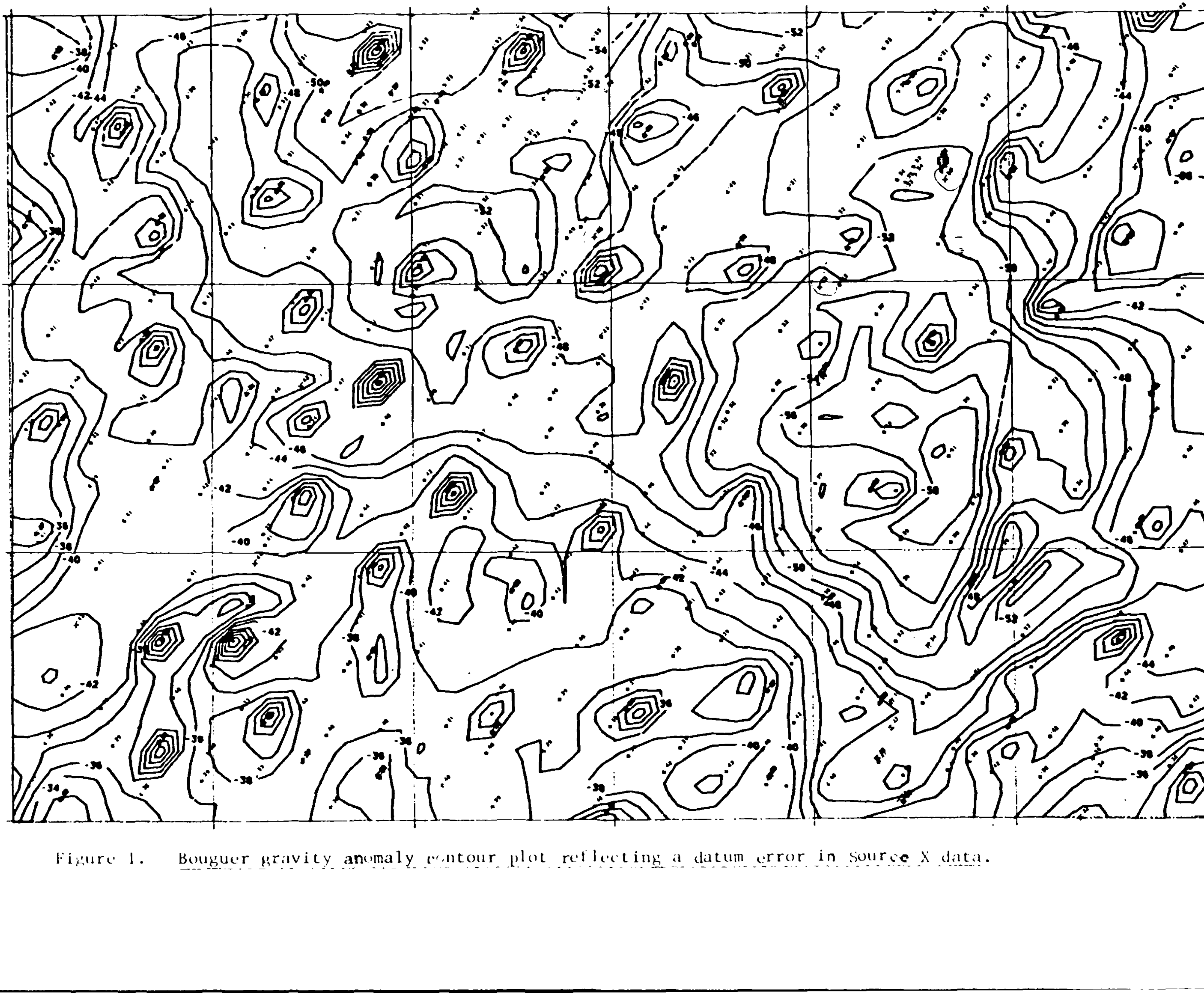

Figure 1. Bouguer gravity anomaly contour plot reflecting a datum error in Source X data.

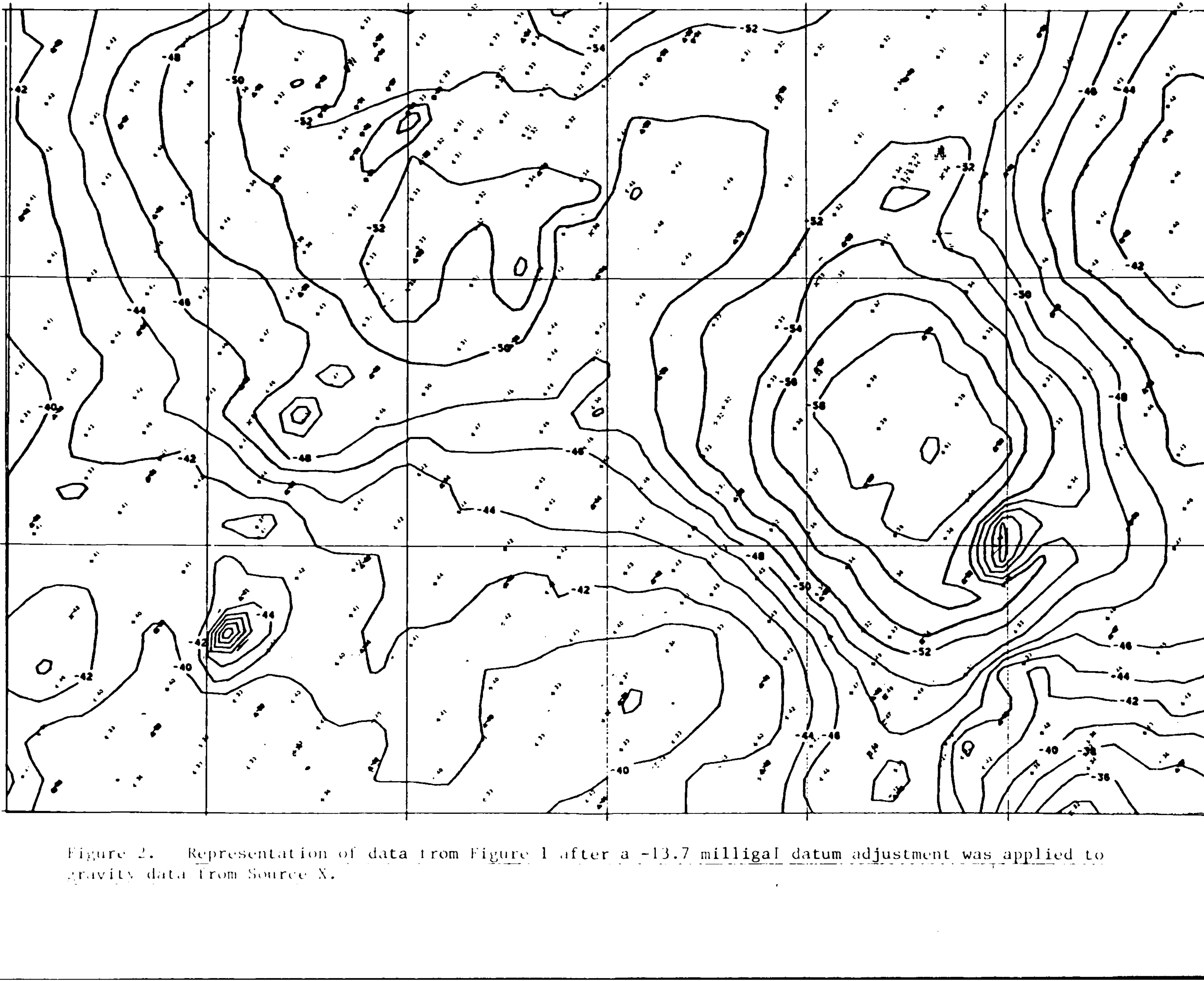

Figure 2. Representation of data from Figure 1 after a -13.7 milligal datum adjustment was applied to gravity data from Source X.

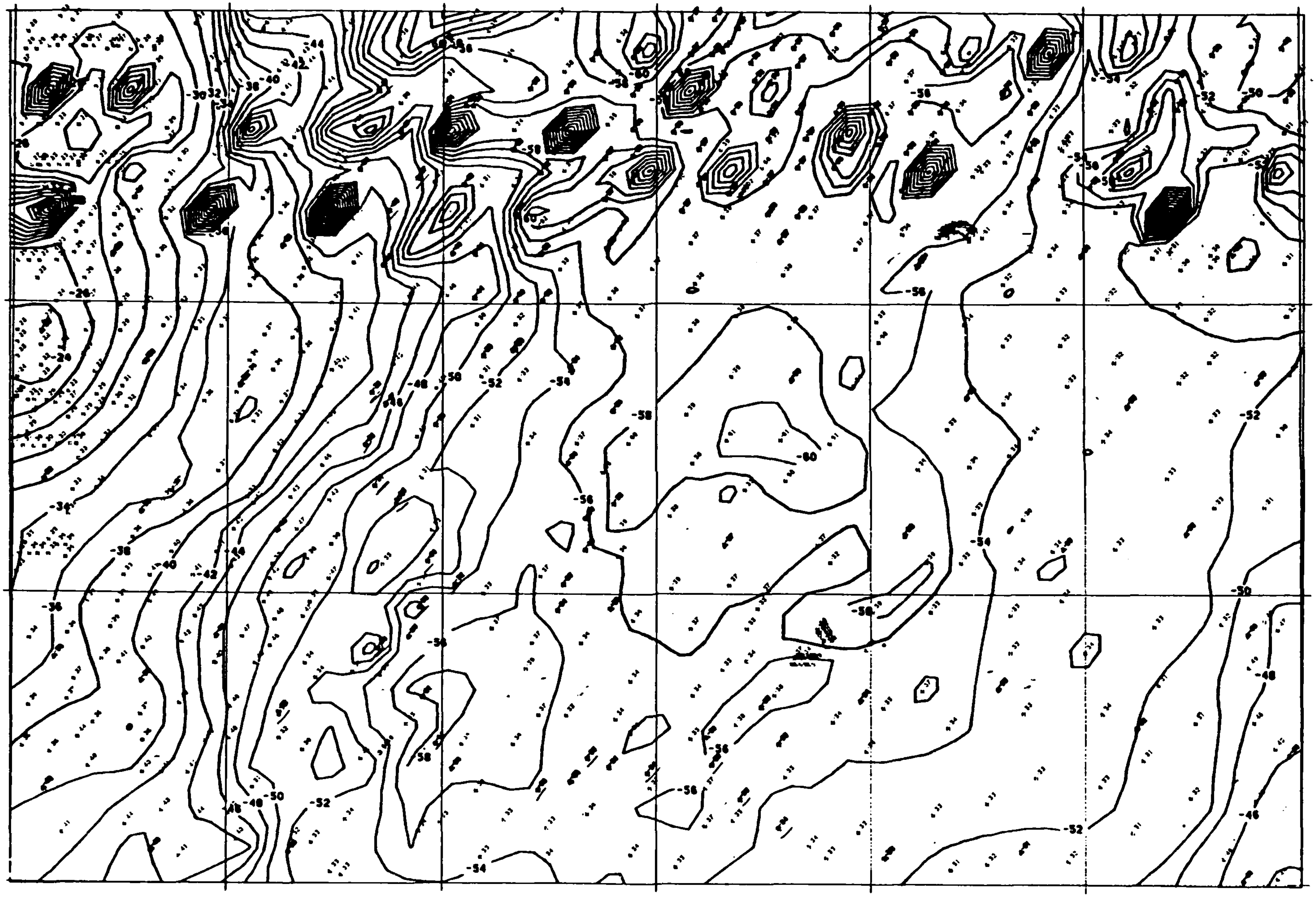

Figure 3. Bouguer gravity anomaly contour plot reflecting an error due to the double reduction of Source Y data.

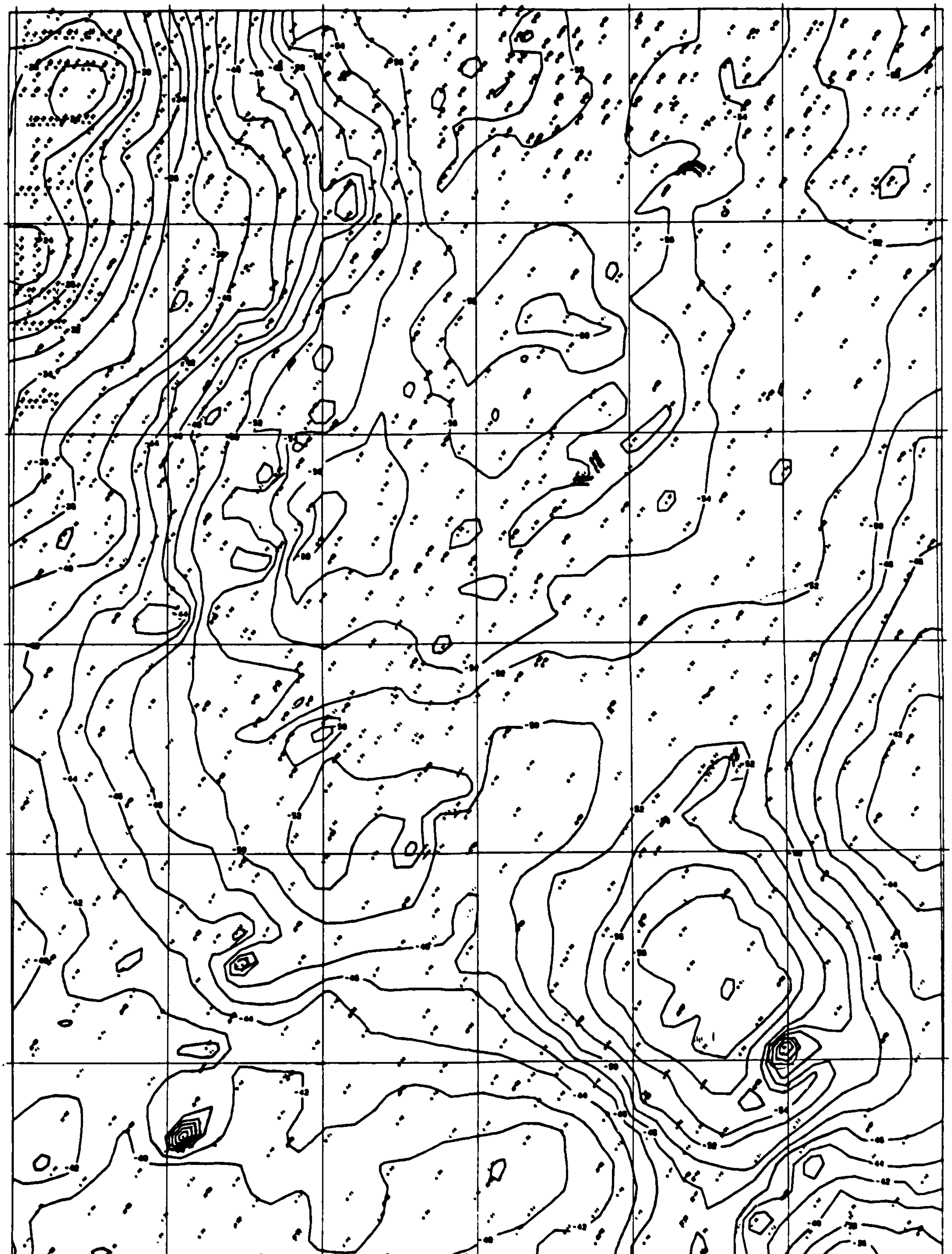

Figure 4. Representation of Figures 1 and 3 using corrected gravity data from Sources X and Y.

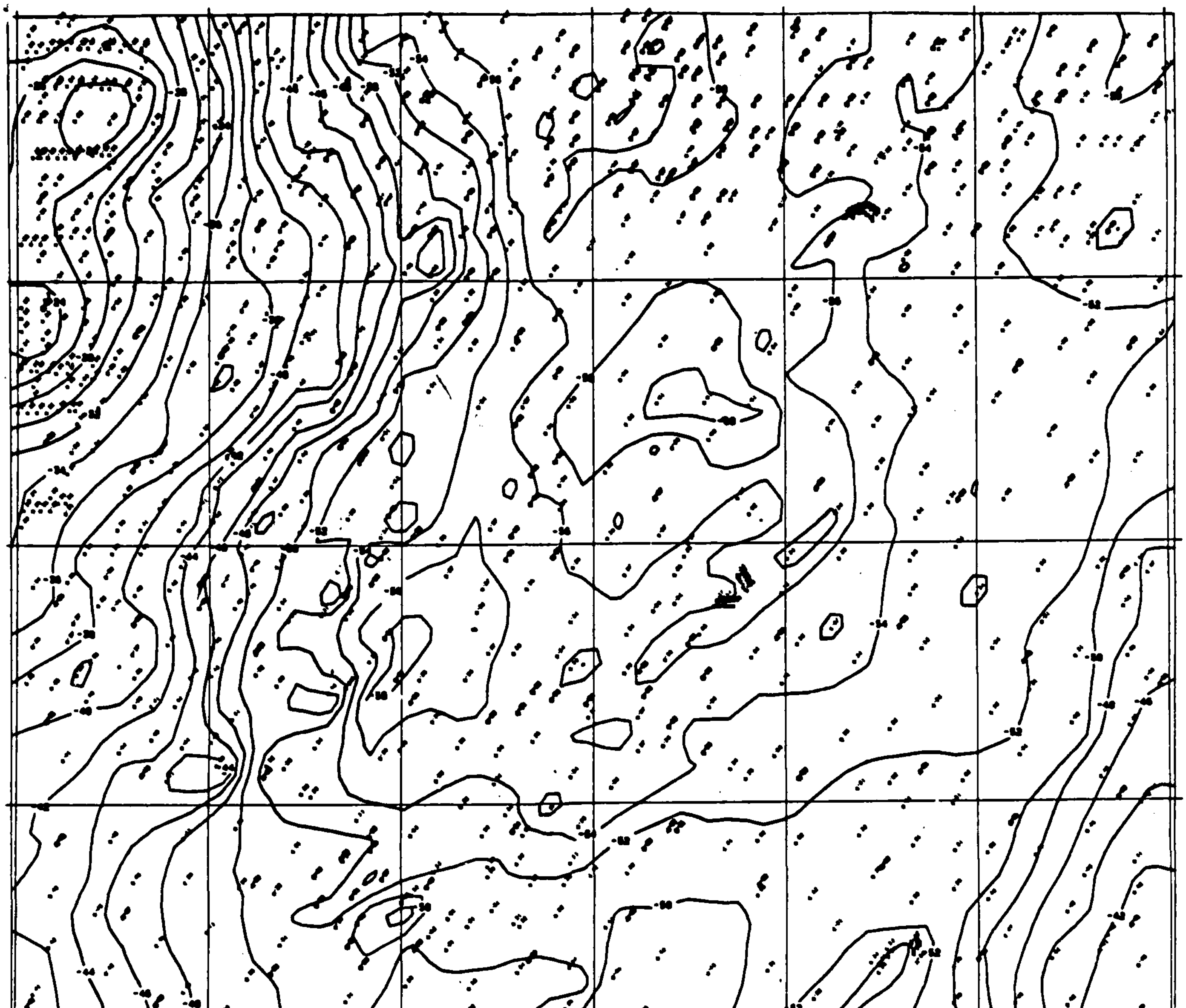

Figure 5. Reflects Figure 4 after the deletion of four "bad" gravity stations.

ACKNOWLEDGEMENTS. The cooperation, advice, and constructive criticism from members of the Evaluation Sections of the Department of Defense Gravity Library made this paper possible. Special thanks are extended to Joseph M. Dicus, Donald F. Lingle, John L. Oglesby, Luman E. Wilcox, and B. Louis Decker for sharing their knowledge, time, and experience.

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